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High-Order vs Low-Order Panel Methods for Unsteady Subsonic Lifting Surfaces

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Introduction

THE purpose of this Note is to clarify the differences between a high-order panel method and a low-order panel method in their applications to steady and oscillating lifting surfaces in subsonic flow. The vortex lattice method is a steady low-order-lifting-surface (LOLS) method proposed by Hedman[1] and Belotserkovskii[2] during the mid-1960s. Its success led to its unsteady-flow extension, the doublet lattice method (DLM), by Albano and Rodden[3] and Rodden et al.[4,5] By "low-order" in LOLS is meant that the singularity (vortex or doublet) distribution is concentrated along the quarter-chord line on each lifting surface box. The choice of the quarter-chord location is perhaps inspired by the exact two-dimensional thin-airfoil solution or borrowed from Prandtl's lifting-line solution (but for an elliptic planform only). By the mid-1970s, Woodward[6] and PANAIR (see Ref. 7) further advanced the lifting theory, in subsonic and supersonic flow, with a fully distributed singularity over the complete box. This is defined as the high-order-lifting-surface (HOLS) method, whereby the singularity kernel is required to be integrated along chordwise and spanwise directions instead of once along the quarter-chord line as for the case of LOLS. ZONA6 (see Ref. 8) is the unsteady extension of Woodward's HOLS theory. It has long been accepted that the HOLS is an advanced version of the LOLS. LOLS, confined by its low-order nature, requires its force point (at which to evaluate pressure) to be fixed with the sending point at the quarter-chord singularity, and consequently its control point is constrained at the three-quarter-chord point in order to achieve accurate solutions. By contrast, HOLS is superior to LOLS in that its force point and control point in principle need not be prefixed, because the singularity is fully distributed. Unlike LOLS, determination of the location of these points in ZONA6 is based on countless numerical experiments for evaluation of numerous wing planforms under various flow conditions. HOLS has a sound theoretical foundation in that its formulation realizes a unified subsonic–supersonic high-order-lifting-surface method as well as a fully extended unified unsteady-flow methodology, namely, ZONA6 and ZONA7 (see Ref. 9). Lacking a sound foundation, LOLS thus far offers no unsteady supersonic counterpart, in spite of several previous attempts. In what follows, we will compare the predictions of the aerodynamic centers, the unsteady pressures, and the generalized aerodynamic forces for rectangular wings with large aspect ratios (AR) and delta wings, generated by HOLS and by LOLS.

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Aerodynamic Center of High-Aspect-Ratio Rectangular Wings

In Ref. 10, the author showed that the aerodynamic center (a.c.) computed by an improved DLM called N5KQ (Ref. 5) is more accurate than that computed by ZONA6 for a rectangular wing of AR 20. It is further claimed that N5KQ also predicts the a.c. at exactly the quarter-chord with one aerodynamic box along the chordwise strip, whereas ZONA6 (referred to in Ref. 1 as CPPM) predicts the a.c. at the 50% chord. This thus led the author[10] to conclude that ZONA6 is an inferior method for flutter and divergence predictions. To clarify this apparent misunderstanding in ZONA6 as a HOLS method as opposed to N5KQ as a LOLS method, we revisit the case of an AR 20 rectangular wing employed in Table 1 of Ref. 10, in which the author intended to show that N5KQ is superior to ZONA6 (with a force point assigned at the 50% chord), consistently predicting the a.c. location at 25% for all chordwise box arrangements including that due to a single box (strip). In Table 1, we show the results of ZONA6 with the force point (f.p.) assigned at the 25% chord. This time, as seen from the last a.c. column, both methods would yield nearly identical a.c. locations for almost all chordwise boxes considered. It can be seen that ZONA6 can also predict the 25% chord of the a.c. with exactly one box on the strip; as the number of boxes increases, ZONA6 predicts a slightly forward a.c. as N5KQ does. However, no exact solution exists for this case to establish which solution set is likely to be more correct.

Aerodynamic Center of Delta Wings

With the planform shape changed, the a.c. location shifts. A low-aspect-ratio wing may have an a.c. location largely different from one around the 25% chord. Here, we consider a delta wing with AR 2.31 at $M = 0.0$ whose a.c. location is obtained at 59.34% of the root chord as derived by the classical theory of Truckenbrodt.[11] Table 2 presents the a.c. locations predicted by ZONA6 (with a f.p. assigned at the 25%, 50%, and 70% chords) and by N5KQ.

As the number of boxes increases, ZONA6 with a f.p. at 70% yields an a.c. at 59.05% of the root chord, which is slightly ahead of the exact a.c. location of the 59.34% root chord. N5KQ predicts an a.c. of 58.40% of the root chord, which is ahead of the theoretical a.c. location.

The examples of Tables 1 and 2 suggest that the best f.p. location is in fact planform dependent. Confined by the LOLS formulation, the f.p. is fixed at the 25% chord for N5KQ. By contrast, ZONA6 has the freedom of assigning f.p. locations for the best a.c. solution. But as an industrial software, the f.p. location in ZONA6 should not be a user input, as it would burden the end user. With all planforms considered, we therefore select a compromise f.p. at 50% as a default value for ZONA6.

Unsteady Pressures on Delta Wings

N5KQ, as a LOLS method, is expected to yield inaccurate solutions for planforms with aerodynamic boxes of large aspect ratios. To alleviate this aspect-ratio restriction on aerodynamic box modeling, it is necessary to increase the order of the vortex-singularity distribution on the aerodynamic boxes. ZONA6, as a HOLS method, employs the constant vortex approach that results in converged solutions with high accuracy. Shown in Fig. 1 are the lifting pressure coefficients (ΔC_p) on a 70-deg delta wing at $M = 0.8$ with two types of aerodynamic box modeling: 10×10 and 40×10. In 10×10 aerodynamic box modeling, the N5KQ solutions break down at the tip strip (station 10), caused by the incompatibility of the LOLS

Table 1 Static longitudinal characteristics of rectangular wing with Æ 2.0 at $M = 0.0$

Division		$C_{L\alpha}$			$(C_{M\alpha})_{0.5}$			a.c. (% chord)		
		ZONA6			ZONA6			ZONA6		
Nc	Ns	f.p. = 0.25	f.p. = 0.50	N5KQ	f.p. = 0.25	f.p. = 0.50	N5KQ	f.p. = 0.25	f.p. = 0.50	N5KQ
1	10	6.335	6.335	5.386	1.584	0.000	1.346	25.00	50.00	25.00
	40	6.231	6.231	5.341	1.558	0.000	1.335	25.00	50.00	25.00
3	10	5.638	5.638	5.392	1.525	1.055	1.359	22.95	31.28	24.79
	40	5.546	5.546	5.351	1.504	1.041	1.351	22.89	31.23	24.76
5	10	5.585	5.585	5.392	1.479	1.200	1.360	23.51	28.52	24.77
	40	5.495	5.495	5.429	1.459	1.184	1.372	23.46	28.46	24.73
10	10	5.561	5.561	5.392	1.441	1.302	1.360	24.09	26.59	24.77
	40	5.471	5.471	5.430	1.421	1.284	1.372	24.03	26.53	24.72
15	10	5.556	5.556	5.392	1.427	1.335	1.361	24.31	25.97	24.77
	40	5.467	5.467	5.430	1.408	1.317	1.373	24.25	25.92	24.72

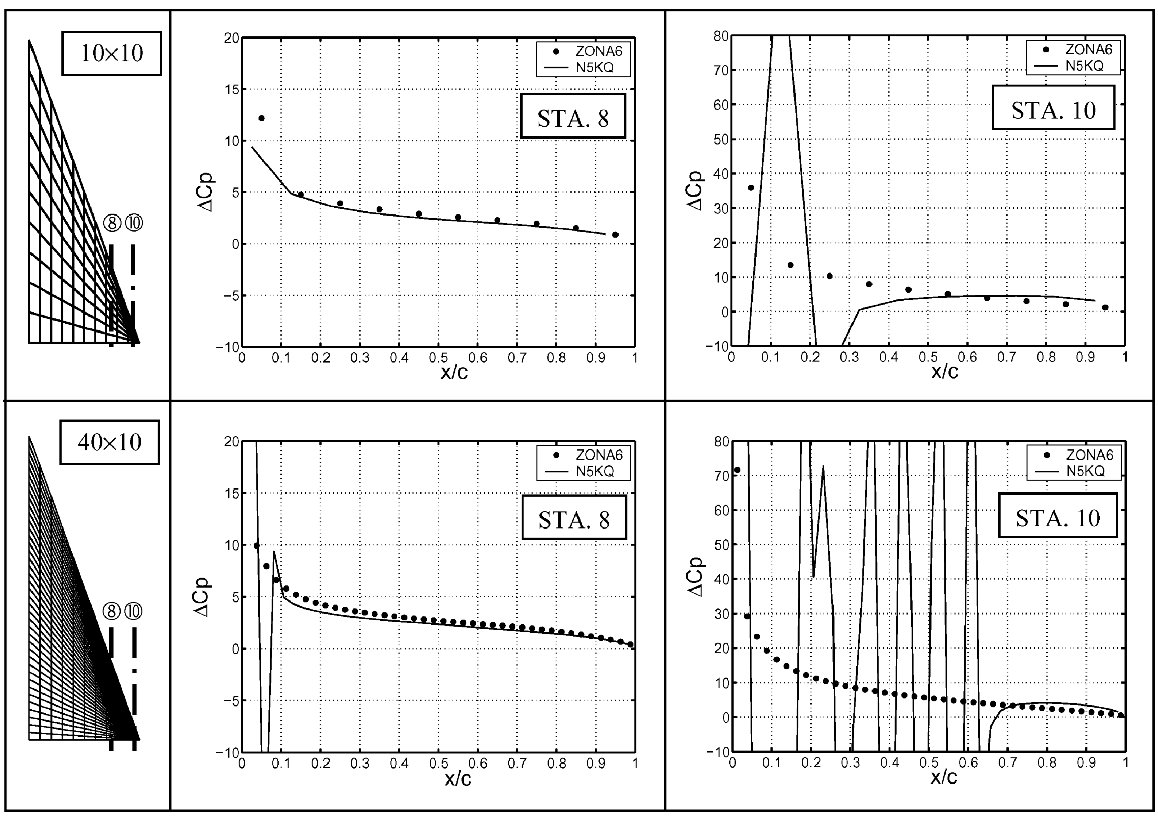

Fig. 1 Lifting pressures on a 70-deg delta wing at $M = 0.8$.

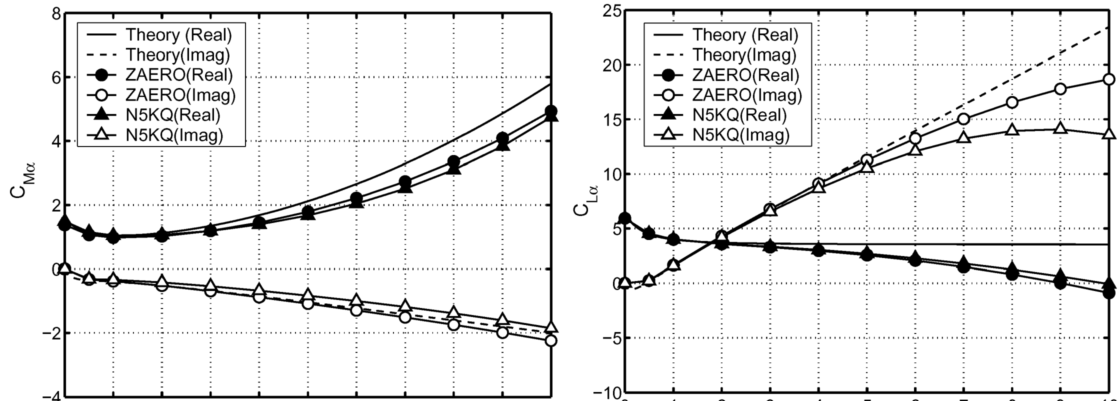

Fig. 2 Unsteady longitudinal stability derivatives of rectangular wing at $M = 0.0$.

Table 2 Aerodynamic center of delta wing with Æ 2.31 at $M = 0.0$

Division (Nc × Ns)	Aerodynamic center (% chord)				
	ZONA6 (force point location)				
	f.p. = 0.25	f.p. = 0.50	f.p. = 0.70	N5KQ	Theory[11]
10 × 10	58.05	59.51	60.68	58.41	
20 × 10	58.30	59.03	59.62	58.55	
20 × 20	58.25	58.99	59.58	58.46	59.34
40 × 10	58.43	58.80	59.09	58.44	
40 × 20	58.39	58.75	59.05	58.40	

method due to the high-aspect-ratio aerodynamic boxes. Ironically, as the number of chordwise boxes increases (40 × 10 modeling), the breakdown of N5KQ becomes more pronounced, caused by the even larger aspect ratio of the tip-strip aerodynamic boxes. By contrast, the lifting pressures predicted by ZONA6 remain smooth; showing method robustness due to the HOLS formulation, as expected.

Generalized Aerodynamic Forces of High-Aspect-Ratio Rectangular Wings

The HOLS approach of ZONA6 is aimed at improving the accuracy of unsteady aerodynamic prediction at high reduced frequency k. To be a robust method, ZONA6 must yield a bounded solution error for all frequencies. As the oscillatory frequency becomes higher, the unsteady wave number passing each box also becomes larger. There are two ways to account for such highly oscillatory waves accurately. One is to render the number of aerodynamic boxes compatible with the wave number, which will increase the computational time; the other is to increase the order of the vortex singularity on each aerodynamic box. The HOLS approach of ZONA6 is clearly the latter, which can yield accurate unsteady pressures and generalized-aerodynamic-force (GAF) solutions while maintaining reasonable computational efficiency. The rigid mode GAFs, $C_{L\alpha}$ and $C_{m\alpha}$, of ZONA6 and N5KQ at various reduced frequencies on an AR-20 rectangular wing are presented in Fig. 2. As the reduced frequency increases ($k > 3.0$) toward the higher end, the imaginary solution of $C_{L\alpha}$ and the real solution of $C_{m\alpha}$ predicted by N5KQ begin to depart further from the Theodorsen-function results than the solutions of ZONA6.

The ZONA6 results in Fig. 1 and 2 were obtained and published[12] some 8 years ago, along with a comparison with results of N5KA, an earlier version of DLM. When ZONA6 is compared here with the recent version of DLM (N5KQ), it appears that no major improvement is found in the N5KQ results. This is expected because both DLM methods inherit the same inadequacy of the low-order-lifting-surface (LOLS) formulation.

Conclusions

According to the previous vortex lattice finding, a low-order lifting surface (LOLS) method is confined to a fixed force-point location and a control-point location at quarter chord and three quarter chord (on each box), respectively. By contrast, a high-order lifting surface (HOLS) method is not required to pre-fix a force point location. Rather, the determination of the force point and control point locations in HOLS is a result of substantial numerical experiments on a large collection of wing planforms and flow conditions. For example, ZONA6 and ZONA7 have settled with the same force point location at mid chord (on each box), but with control points located at 0.85 chord and 0.95 chord, respectively. This certainly gives a HOLS method like ZONA6 an advantage over a LOLS method like N5KQ (DLM) to achieve higher accuracies and cover wider range of aeroelastic applications. A comparative study is presented wherein the solution accuracy and robustness of both methods in terms of the aerodynamic center (a.c.), the unsteady pressures and the generalized aerodynamic forces for four wing planforms clearly elucidate the superiority of the HOLS methodology.

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Flight-Path Reconstruction Using Numerical Optimization

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Introduction

FLIGHT-TESTING of aircraft without an innate data recorder requires other means to acquire flight-path data. A low-cost solution is a hand-held global positioning system (GPS) receiver, possibly augmented by an inertial measurement unit (IMU).

The Department of Aeronautics has for some time been involved in flight-testing of optimal trajectories.[1–3] During the initial tests of optimal trajectories using GPS as the only recording device, it was investigated whether the use of GPS also could be suitable for the basic flight training that uses the Saab 105, designated SK60.[4] These aircraft were made operative in the late 1960s and have no means of recording state variables during flight that would make it possible to evaluate the training sessions afterward. Consequently, it would be very desirable to introduce such capabilities during basic flight training.

The present paper describes some of the efforts spent on developing a useful flight postprocessing system using GPS as the only recording device. First, an optimization method for finding a smooth

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